A 350KV DUAL RESONANT TRANSFORMER FOR CHARGING A 40PF PFL AT KILO-HERTZ REP-RATES

M.C.Scott
Maxwell Laboratories, Inc.
Albuquerque Division
P.O. Box 9350
Albuquerque, NM 87119

J.P. O'Loughlin and R.P. Copeland
USAF PL/WSR
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

ABSTRACT

A dual resonant transformer, capable of charging a 40 pF pulse forming line to 350 kV, has been developed. Peak repetition rates of two kilo-Hertz have been obtained with the use of a self break high pressure hydrogen spark gap switch. The primary energy store of the device consists of 17.6 nF at 30 kV. This paper will discuss the design of the transformer, the development of the high pressure hydrogen switch, and the use of a high pressure SF6 environment to house the pulse transformer. Also the method used to repetitively charge the primary energy store will be presented. Data obtained under rep-rate operation will be shown to illustrate repeatability of the self break voltage and the subsequent output voltage pulse of the transformer.

INTRODUCTION

A dual resonant transformer has many desirable characteristics for charging low capacitance pulse forming lines (PFL) to high voltages[1]. It can be made very compact, the primary energy store is held to relatively low voltages, and for high rep-rates it is appealing because only one switch is necessary to deliver the stored energy to the primary winding. Energy transfer efficiency, to the PFL can ideally approach 100 %. In this case approximately 30% was achieved. Efficiency is quickly degraded by mismatches in the primary and secondary resonances, but is also decreased due to stray capacitance of the secondary, and RF losses in the secondary. In this particular example, a coupling coefficient of 0.6 was chosen, as it allowed respectable step-up, with the necessary spacing between the primary and secondary windings. Sufficient spacing between the primary and secondary windings is required for voltage hold-off and also helps minimize capacitive loading on the secondary.

The high pressure hydrogen spark-gap was chosen in light of results obtained by the Naval Surface Warfare Center[2]. It also has the advantages of compactness, high power handling, low inductance, simplicity and low cost. Initially, a trigatron triggering scheme was employed in the switch, but due to trigger pin heating effects, a self break approach was pursued.

TRANSFORMER DESIGN AND EXPERIMENTAL CONFIGURATION

The transformer was designed in several prototypical stages. Initial transformer development, was performed on a machine using a hydrogen thyratron, and capacitor assembly housed in an oil vessel feeding the transformer assembly enclosed in a second oil chamber. This made for a circuit having a rather large value of added circuit inductance compared to the primary inductance of the transformer. In this setup, either more inductance was necessary in the secondary, or the primary capacitance could be decreased to match the resonant frequencies. Neither of these solutions were desirable, as they either increased the stray capacitance or decreased the initial energy store respectively. As mentioned, it

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A dual resonant transformer, capable of charging a 40 pF pulse forming line to 350 kV, has been developed. Peak repetition rates of two kilo-Hertz have been obtained with the use of a self break high pressure hydrogen spark gap switch. The primary energy store of the device consists of 17.6 nF at 30 kV. This paper will discuss the design of the transformer, the development of the high pressure hydrogen switch, and the use of a high pressure SF6 environment to house the pulse transformer. Also the method used to repetitively charge the primary energy store will be presented. Data obtained under rep-rate operation will be shown to illustrate repeatability of the self break voltage and the subsequent output voltage pulse of the transformer.

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appeared feasible to replace the thyratron switch with a hydrogen spark gap and thus build a much more compact energy store / switch / pulse transformer assembly.

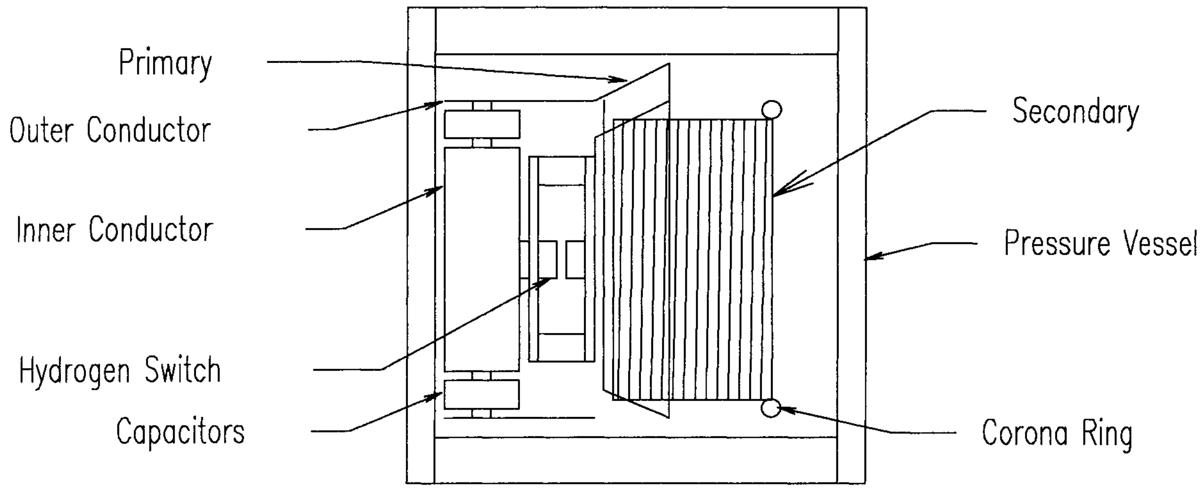


Figure 1 Pulse Transformer Assembly

Figure 1 illustrates the pulser configuration obtained. Central to the assembly is the hydrogen switch. It is surrounded by a ring of eight TDK 2.2 nF, 40 kV barium titanate capacitors. The capacitors are mounted on a 15.24 cm. diameter tube and are surrounded by an octagon shaped outer metal sheet of 3.18 mm. aluminum. The capacitors, inner and outer conductors and the switch, form a coaxial pulser assembly, upon which is immediately mounted the conically shaped primary winding. The 7.62 cm. wide, 22.86 cm. mean diameter conical spiral winding has approximately 330 nH of inductance, measured at 100 kHz on an inductance bridge. The conical shape was chosen to move the primary winding away from the output end of the secondary to minimize capacitive coupling and voltage stress between the output terminal and the relative ground of the primary winding. The secondary winding consists of 40 turns of 16 AWG, 600 VAC, teflon coated stranded copper wire. This wire is wound on a 17.8 cm. diameter by 11.43 cm. long acrylic tube. This secondary diameter to height ratio yields a secondary with approximately 245 uH of inductance, measured at 100 kHz on an inductance bridge and 20 pF of stray capacity, isotropic and turn to turn combined. At the output end of the secondary a 9.5 mm. diameter corona ring formed from copper tubing protects the last windings from the high voltage stress while not adding too much stray capacitance.

The high pressure hydrogen switch consists of an 3.81 cm. wall, 15.24 cm. o.d. acrylic housing sandwiched between two 6.35 mm. aluminum plates. Buna-N o-rings are used to make the aluminum plate to acrylic seal and eight 9.53 mm. diameter G-10 threaded rods are used to hold the switch assembly together. The switch has been pressure tested to 300 p.s.i.g., but when housed in the SF6 vessel, itself pressurized to 250 p.s.i.g., the hydrogen switch is not greatly stressed. Initially, 1.9 cm. diameter brass electrodes were tried in the switch. The electrodes had a Rogowski profile on the opposing surfaces. The gap spacing was optimized to 2 mm., requiring a hydrogen pressure of 275 p.s.i.g. at 30kV charge levels. The brass performed well in repeatability studies, but when high rep-rate long bursts were performed, erosion rates were unsatisfactory and large amounts of black deposits were left inside the switch. Copper-tungsten, 80%-20%, inserts were machined into the brass electrodes, with the same profile. Operation with this material greatly improved the longevity of the electrodes. Even long running cycles, 1 kHz for three minutes, yielded no discernable erosion of the electrode surfaces, only a polishing of the electrode surface, apparently caused by copper migrating to the surface of the electrode. After the long running cycle, the pulser was disassembled and the switch housing was only slightly warm to the touch.

Charging of the 17.6 nF capacitor bank was performed using two Maxwell CCDS 30 kV, 8 kJ/sec, switching power supplies running in parallel. The power supplies were externally switched on and off using the external gating feature. A normally high TTL level signal on the gating input disables the

high voltage output of the supplies. A Stanford Research DG 535 pulse generator was used to apply low level signals to the gating input for a time only long enough to get the capacitors to the desired voltage level. The DG 535 was externally triggered by a second pulse generator, providing the rep-rate and burst length input. Using the two CCDS supplies, the charging time was approximately 400 uS for 30 kV on 17.6 nF, as the supplies were custom modified, by the manufacturer, to provide 10 kJ/sec for the first 10 seconds of on time. Unlike the gating scheme used in Reference 1, in which switch light was used as an indicator of switch discharge and subsequently synched the gating pulses, the gating pulses in this experiment were free running, yielding open loop charging. Gating the power supplies open loop caused the charging pulses to become out of step at times. The delay after discharge feature of the supplies, 100 uS, would allow recovery of the switch, even though a remaining portion of the gating pulse might charge the capacitor bank to some intermediate level below the self break voltage of the switch. Even though this undesirable effect occurred, the self break voltage regulation remained acceptable.

The simulated circuit is shown in Figure 2. In this circuit Cpr is the initial energy store capacitance of 17.6 nF, Lstr is the stray inductance of the primary circuit at 80 nH. The coupling coefficient of the transformer is 0.6, yielding L1-M = -3 uH, L2-M = 141 uH, and M = 3.2 uH. The effect of the stray inductance is to decrease the effective coupling of the circuit to 0.5. Rsec is

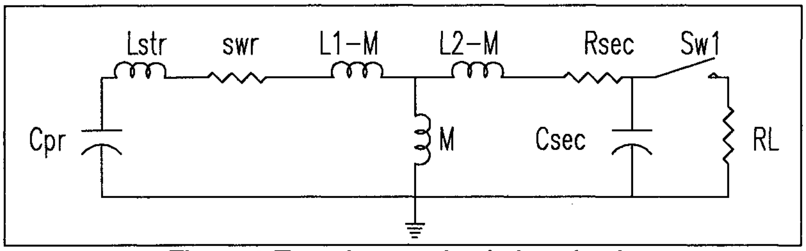


Figure 2 Transformer simulation circuit.

simulated RF resistance of the secondary coil at 20 ohms, and Csec is both the PFL capacitance and secondary stray capacitance with a value of 60 pF. It may be noticed that the primary and secondary inductance values are different from the values measured at 100 kHz. In operation the primary and secondary inductances diminished by approximately 40% each. A small portion of this reduction can be accounted for by the difference in measurement frequency versus the operational frequency of 3.4 Mhz, however most of the inductance decrease is caused by flux exclusion due to the proximity of the circular aluminum plate on the switch housing. This effect has been cross checked with the inductance bridge and at 100 kHz decreased the inductances by 25% under values measured far from any metal surfaces. The resonant frequencies of the circuit increased by 20 %. With the circuit model reflecting the flux excluded operating inductances, at a 30 kV charge voltage, the output pulse in Figure 3 was produced.

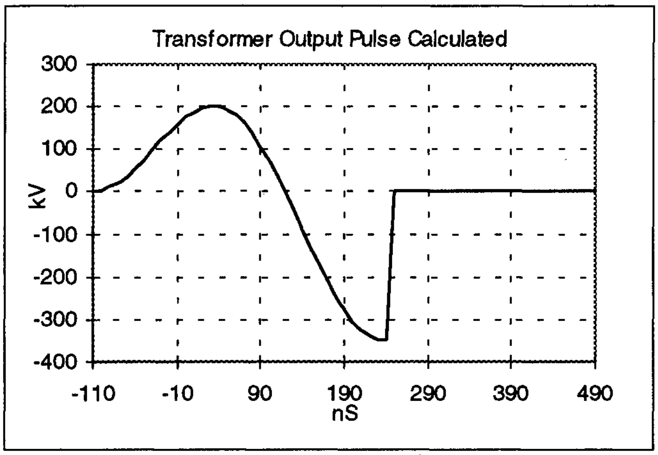


Figure 3 Calculated Output of the Transformer.

EXPERIMENTAL DATA

A typical output pulse of the transformer is shown in Figure 4. This pulse is at a 30 kV charge level and is charging the 40 pF PFL. The sharp decline in the pulse immediately following the negative peak is due to the discharge of the PFL through its output peaking switch.

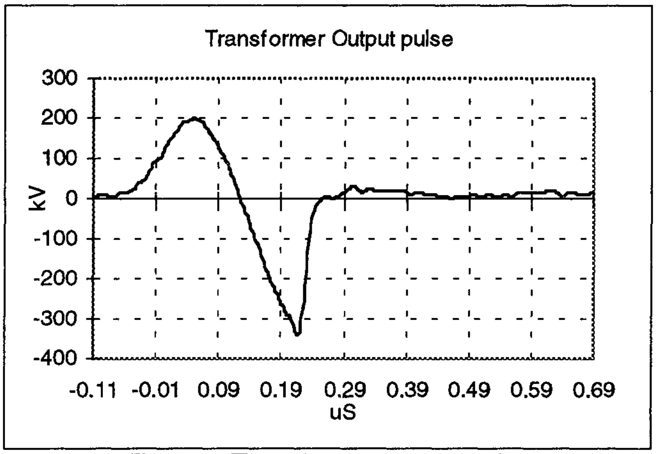


Figure 4 Transformer output pulse.

The rep-rate data displayed in figures 5 through 8 are charging waveforms measured with a Northstar 60 kV 1000 X pulse voltage probe. The probe placement is on the power supply side of a 50 ohm line termination resistor, between the center and outer conductors of a 50 ohm 214 charge cable. Figure 5 is a four pulse burst at a 500 Hz rep-rate. Short bursts are shown here for clarity, but the self-break voltage levels are representative of any pulse burst length.

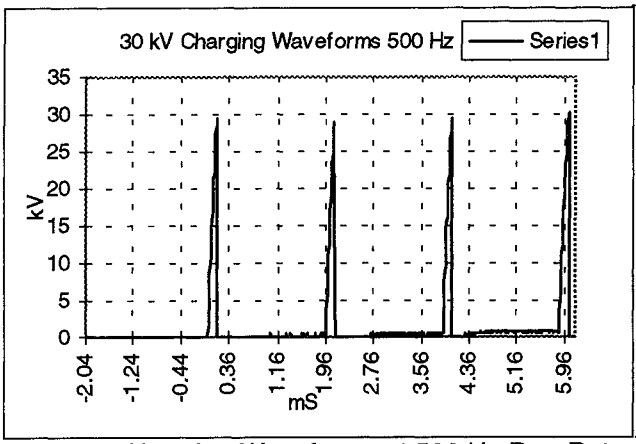


Figure 5 Charging Waveforms at 500 Hz Rep-Rate.

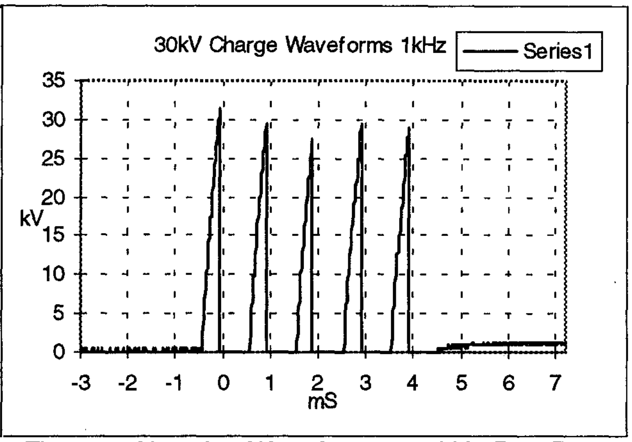
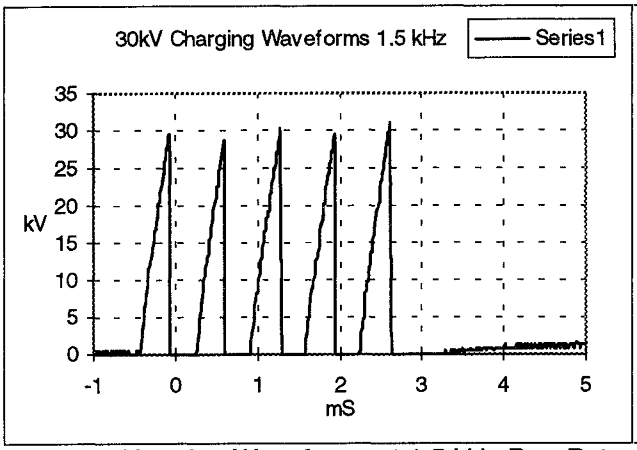


Figure 6 Charging Waveforms at 1kHz Rep-Rate.

At the 500 Hz rep-rate self break voltage repeatability can be seen to be running about +/- 1 kV pulse to pulse. Figure 6 is a five pulse burst at a 1 kHz rep-rate. This pulse train is fairly representative of operation at this rep-rate with self break repeatability normally running +/- 2 kV of the desired level. Figure 7 is a set of charging waveforms at 1.5 kHz rep-rate again showing that the self break voltage lies within +/- 2 kV of the desired value. In figure 8 the repeatability is seen to be degrading with charge values lying within the +2/-6 kV range of a 30 kV charge setting. This is typical for short bursts of 100 pulses or less.



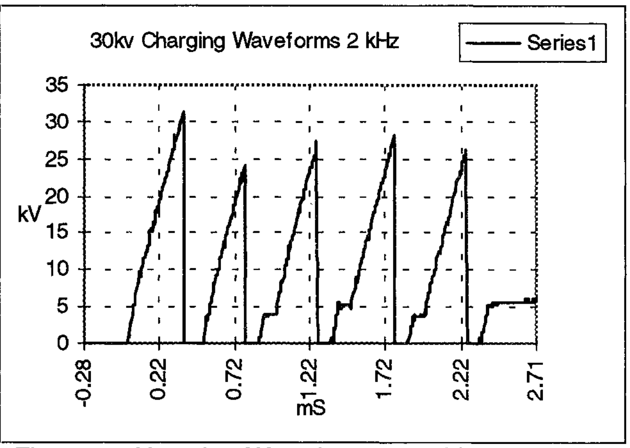


Figure 7 Charging Waveforms at 1.5 kHz Rep-Rate. Figure 8. Charging Waveforms at 2 kHz Rep-Rate.

Operation at 2 kHz for longer bursts showed further degradation of the charge level, which on a 300 pulse burst would decrease from 30 kV to 20 kV presumably due to heating of the hydrogen gas or electrode surfaces in the switch. One supposition is that the ragged results of self break voltage repeatability may not be totally due to switch recovery. Since there is a 100 us delay after discharge before the power supplies can start recharging and it takes approximately 400us to recharge the capacitors, the charging waveforms easily become out of sync with the gating pulses. This is noted by the step in the charging waveforms in Figure 8 on pulses 3,4 and 5. The intermediate voltage level on the capacitors is produced by the tail end of the previous gating pulse and the continuation of charge is produced 100us later on the successive gating pulse. Some of the lower voltage charge levels may be caused when a portion of the gating pulse is effectively canceled out by the delay after discharge off time.

In figure 9 three transformer output pulses, acquired randomly during a 1 kHz rep-rate by arming a TEK 2430 during a pulse burst, are presented to show the variation in output voltage due to the deviation in charging self break voltages.

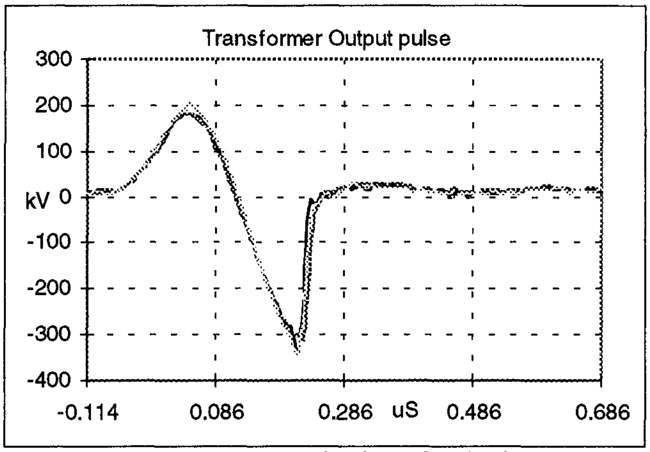


Figure 9 Transformer outputs acquired randomly during a 1 kHz burst.

An SF6 pressure vessel was used to house the transformer assembly. A gas insulator was chosen over oil due to breakdown of the oil experienced under high rep-rate conditions and also because of the lower dielectric constant of gas over oil. A lower dielectric constant surrounding the transformer secondary results in less capacitive loading of the secondary. At 30 kV, 1kHz rep-rates and higher it was necessary to pressurize the vessel to 250 p.s.i.g. of SF6, while at low rep-rates, 100 to 200 Hz, 100 p.s.i.g. was sufficient.

On the 10cm. long secondary, 350 kV output developed 35 kV/cm. stresses across the winding. The 16 AWG, 600 VAC, teflon coated, stranded wire easily withstood the 8.75 kV turn to turn stresses at the 3.4 Mhz resonant frequency.

Aluminum is the desirable conductor to use in a high pressure SF6 environment. If copper is necessary as in the case of the primary winding and the corona ring in this experiment, it should be coated with an enamel paint, as copper quickly corodes in this atmosphere.

CONCLUSIONS

The double tuned resonant transformer is a good method for charging low capacitance PFLs under high rep-rate conditions. It is simple, reasonably efficient and very reliable. This pulser has undergone several tens of hours of cumulative rep-rate operation with little to no maintenance on either the transformer secondary or the high pressure hydrogen switch. Triggering of the switch is desirable in some applications and work towards that goal is continuing. If the variation in output voltage and the set-up time required for tuning in the self break switch can be tolerated, that is currently the most uncomplicated, infallible route to take.

Work is in progress on a second generation of this type of resonant transformer. The key differences are 52.8 nF of energy store capacitance at 50 kV, and the output voltage is to approach 1 mega-volt on a 40 pF PFL. Energy transfer efficiency has become a key goal in pursuit of this result.

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